Circuit and Electromagnetic System Design Notes
Note 17
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HUN Lecture No. 5

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x = Major Item

ODDS AND SODS

x Monitoring:
  a Voltage
  b Current
x Safety.
Modelling.
$CuSO_4$ resistors as:
  a Dump resistors
  b Charging resistors.
Measuring resistance of liquid resistors.
Cheap grading structures.
x Quick constructional techniques, of use in high voltage generators.
Running up a high voltage generator - desirable safety factors.
Fault modes.

EXTRA TOPICS POSSIBLY TO BE COVERED
(if the lecturer is prepared to make a fool of himself)

The direct pumping of gas mixtures.
Features that seem to be important in delaying sparking.
Conceivable approaches to improved energy density pumping.

LECTURE No. 5

VOLTAGE MONITORING

The section in NPT notes should be consulted. A flexible copper sulphate solution high voltage divider is described in reference 1. This monitor can be curved in the way described in NPT notes so as to reduce the integrating effect of its stray capacity to a minimum.

The alternative approach of capacitor dividers or E field probes as they are sometimes known, has not been used in the SSWA division much but has been employed in a number of situations by other groups. In the event that references to these are required, a request to us should be made. The major disadvantage as far as we are concerned with this approach is the output signal tends to be at a low level and a rather pick-up free recording system is an essential.

CURRENT MONITORING

Circuit shunts have been the method most used by us. For large current low voltage banks, thin brass sheet low inductance resistors have been used to date, but the tendency is now to move over to Rogowski loops, integrating or otherwise. For more modest currents 100 k amps and below, we have used rings or strips of many 10 ohm resistors in parallel. Where the current is possibly asymmetric a number of outputs (usually 4 suffice) are taken off and mixed. This averages the current across the shunt and can produce answers to a couple of per cent even when the current distribution across the shunt varies by up to a factor of two. The advantage of using current shunts is that again the signal is produced at a level of a few kV. Integrating Rogowski coils tend to produce output waveforms a couple of orders of magnitude lower. Both approaches have various effects which reduce the accuracy of the current measurement and purity of waveform. In the current shunt these are primarily the inductance of the resistor array and to a lesser extent internal capacity effects. With the Rogowski coil approach the internal resistance of the coil and its self capacity enters and the effects of these and other limitations are rather subtler and less readily appreciated perhaps.

SAFETY

NPT notes should be consulted and it should be re-emphasised that it is to be taken seriously. The major real risks are the DC charge on the capacitors and high current power packs. The nominal lower lethal limit is 50 joules for a worst case but discharges of lower than this can be quite unpleasant when they flow through the experimenter. There are a number of cases in the literature of people being involved in accidents with many impulse generators of up to 25 kilojoules stored energy at several million volts and in all cases that I know of the unfortunate recipient survived. This is possibly because the current flows on the outside of the body but more importantly because of its short duration. Thus empirically the pulse aspects of high voltage systems are probably less dangerous than those connected with the DC charged condensers which drive them. However, accidents involving the pulsed voltage output can be painful and potentially dangerous.

Many of the systems we now build are so heavily insulated that it is not possible to find points on which to hang an earthing probe, as is suggested in the NPT note. A slightly modified approach is employed in such systems, which are obviously safer against accidentally touching a capacitor terminal with a few kV residual charge on it.

As before, the first line of defence is the charging voltage meter or meters. These record the volts on the capacitors and power pack and have to operate each time the system is charged. If they become inoperable the system must not be used (it is of course not very sensible to try and use it in this state, safety consideration apart). On firing the system it is checked that they have dropped to near zero. The entry to the caged area is via a door or other barrier and when this is opened a gravity operated ball shorts out both the power pack and the condensers in the bank or marx. At this stage it is checked that the meters do in fact go to zero. In addition the mains volts to the power pack is routed via the door or barrier so that in order to open it, the mains supply to the power pack is broken and this cannot then be operated by accident. As there is now only one dump in the system, the integrity of the lead from the power pack to the condensers has to be insured, and in particular it has to be arranged so that it cannot be pulled out at either end by accident. Even if this were to happen, the power pack meters would show a rapid charging rate or discontinuous charging behaviour with sparking at the partially opened plug and warn the experimenter, as he charges the capacitors. Only copper sulphate resistors are included (usually in the marx charging columns) in the charging leads, as these can be easily seen to be intact. Solid resistors are not used in these links because they can go open circuit without any obvious external signs. In a heavily insulated marx, as has been mentioned, there may be no access to the high voltage conductors on which to hand a shorting stick. However, when the system is being repaired or taken apart, a shorting stick can be used to shorts placed across the condenser terminals as these become available. In addition a high impedance bleed is always present to discharge the low value leakage currents which recharge the condensers after they have been used (the voltage monitor chain can frequently fulfil this requirement).

When a pulse charged capacitor is being disassembled, the mylar sheets out of which it is made can have significant local deposited charges on them, making the disassembly process mildly painful but not directly dangerous. A procedure for combating this is outlined in reference 2. The same difficulty applies to any system where localised charges are deposited on high resistivity surfaces to prevent tracking, a last resort to avoiding small but unpleasant shocks is some sort of earthed metal gloves or their equivalent. The real danger from such discharges is that they may cause someone to drop a heavy weight on himself or to jump or fall over and damage himself mechanically.

MODELLING

Most single dielectric breakdown fields scale (area/volume effects apart) consequently scaled models can give quickly and cheaply any required data on breakdown voltage. In general however the breakdown fields can be calculated to an accuracy adequate for system design purposes. However, sometimes portions of the systems with complex geometry may not be easily treatable and a scale model may be useful in designing these sections so that they are adequately safe. In addition it is of course much quicker to work out ad hoc solutions on a small arrangement, than on a large fully engineered system. Surface tracking may not scale but to a first order linear scaling applies; however it would be possible dangerous to scale by factors of more than 2 or 3. However, there is one sense in which tracking problems are worth looking at on a scaled model and that is the case when the model does track, this almost invariably means that on the full scale tracking will occur and that remedial action is essential. In general it is not necessary to make slavishly exact scale models and indeed the models can be intentionally distorted to emphasies the effect feared or to be studied. Frequently scale models will show that cruder solutions than those initially envisioned may be perfectly adequate and then the time and effort spent in modelling can be recouped manyfold.

In electromagnetic wave propagation problems, scaling is exact and the only limit to the scale used is the response time of the pulse monitoring equipment, the bandwidth of which has to improve as the scale factor. However, frequently it is details of the top and tail of the waveform which are of importance and the rise time of the pulse in the model need not then be exactly scaled.

In order to build small models of high voltage pulse systems, water with its low velocity of light can be used to reduce the length, compared with that of, say, transformer oil or air systems. Of course in this case the model would not necessarily be a linear scale but could be physically distorted to scale various features of the full low dielectric filled generator.

The effect of transitions, mixed dielectric media, bends in finite width strip transmission lines etc can all be studied in small scale systems operating in water, whose length can be quite modest without requiring the use of wide band width sampling scopes.

While the inductance of a marx can be estimated to 20% or so quickly, to get a more accurate evaluation or to compare two arrangements, scaled models of the conductor layout can be made in half an hour or so using plastics and cardboard, covered by aluminium foil then stuck down. The inductance of these scaled models is most easily measured by ringing a 10 kV low inductance capacitor into them, when any poor joints will spark over. The capacity should be chosen so the ringing frequency is scaled from the real systems fundamental frequency, in which case the current paths should be the same in the model as in the full system.

Modelling, when intelligently carried out, can be a very powerful method of solving problems in a few hours which would otherwise require weeks of calculations, calculations moreover which are frequently only approximations to what is really going on, sometimes fatally inadequate ones. Intelligent modelling enables nature to do the hard work.

COPPER SULPHATE RESISTORS

When these are used as dump or charging resistors they should be made leak proof and also be readily visible so that it can be checked that they are properly full. If they are constructed of flexible tube they will take rapid temperature rises of 25 to 30°C and not come to any harm. If they are in rigid walled tubes (typically perspex tubes) the rapid deposition of energy leads to a pressure pulse when the time of deposition is less than the velocity of sound transits across the radius of the tube, since the liquid cannot expand. This can lead to cracking and, in extreme cases, shattering of the containing tube. Typically with 5 mm wall tube up to 75 mm OD we restrict the temperature rise to less than 2°C. For larger tubes or thinner walls 1°C rise may be all that can be tolerated. When copper sulphate solution resistors are employed as charging columns for high energy systems, ionic transfer occurs. This leads to a layer of sulphuric acid being produced at one end of a simple tube with copper end electrodes while distilled water accumulates at the other electrode. If the resistor is vertical this state of affairs is unstable when the positive electrode is uppermost and the layers remix. However when the charging polarity is the other way round a stable situation may result. Sparking can then occur at the top, water isolated, electrode and the copper is deposited in a black tree like growth. The situation can be eased by mounting the resistor horizontally, or by making the electrodes out of cylinders. In the case of a chain of resistors, these can be conveniently made out of a single tube of perspex or flexible PVC, and the intermediate electrodes are arranged so as not to block the tube completely. The individual separated layers then easily mix, except for the electrode at the top of the column and a reservoir of liquid is provided above this electrode. This above difficulty is usually only encountered in very large energy systems, or those with a fairly rapid rate of firing, but can be met where very small diameter liquid resistors are used.

With regard to measuring the resistance of a copper sulphate solution resistor the high voltage pulse value is well defined and constant apart from a temperature coefficient of resistivity. However, a low voltage calibration measurement can be well out because of polarisation effects and electrolytically deposited insulating films on the metal electrodes, reference 3 covers these effects in part.

CHEAP GRADING STRUCTURES

An outline of these is given in reference 4. No very great accuracy is required in producing the contours, in general a pleasingly smooth surface based upon an intuitive solution of Laplaces equation is quite satisfactory. Playing around with an electrolytic tank for an hour or so can rapidly give one the necessary intuition as to the sort of surfaces needed and how sensitive the folds on them are to departures from the optimum.

QUICK CONSTRUCTIONAL TECHNIQUES

In general we stick, glue or use cold setting simplex for nearly all of our constructional work in the high voltage field. Simplex can mechanically join perspex tube and sheet as strongly as the parent material can stand. Thickish pellets of set simplex have a good hold off voltage and while electrically weaker than perspex of the same thickness, are not grossly so.

While evostick or other impact adhesives can be used to stick mylar sheets together, etc (see reference 5), Twin Stik (a double sided tape) is much quicker, although more expensive by a considerable factor. (See reference 6.)

We also use quite a lot of a cloth based tropicalised black tape to hold things together, and it is worth learning how to attach such tape so that it does not slide off under tension over a period of time, a little thought can repay itself many fold. Properly applied such tape can take a lot of tension over an indefinite time and has the advantage of distributing the force over a large area rather than concentrating it in a few places as would screws or bolts.

Occasionally PVC tape is used, this has a significant degree of stretch and many turns of it can apply a large compressional force, which is not released as the compressed member contracts a per cent or so.

The great advantage of these quick and dirty assembly techniques is that modest systems can be built in a few days, and do not need to call on sophisticated engineering support. Frequently perspex sheet can be scored and quickly cracked in a sheet metal bender into the required shapes. Perspex, in reasonably thin sheets, can also be warmed in a gas flame and bent or moulded into more complex shapes before assembly by simplexing. These shapes can be made quickly which would be prohibitively expensive to make out of solid. In addition not infrequently the result of the quick and dirty techniques, can be better than could have been achieved by a more standard engineering approach (see the details of the peaking capacitor in reference 2). Also the use of metal bolts or screws in high voltage systems can give rise to breakdown or tracking problems which may be very difficult to circumvent and while nylon and other plastic screws are available and sometimes used by us, the necessary hole through a perspex sheet can likewise give a lot of trouble.

RUNNING UP HIGH VOLTAGE GENERATORS

In general we follow over-test procedures wherever possible, rather than firing a large number of test shots at the nominal maximum rating of the system. Thus in testing capacitors we do not fire 4000 shots to weed-out the few per cent of weak components but overtest in peak current$^{(i)}$ and impulse ($\int i^2 dt$) by substantial factors for say ten shots. These tests are followed by the re-application of the maximum over voltage test that the manufacturers use to show up an incipient fault growing because of the above tests.

Because surface track-over is a rather variable phenomenon (σ is frequently 10% to 15%) it is very desirable to have a healthy safety margin against it. Typically we would aim for a safety factor of at least a factor of 2 in systems up to 100 kV, 1 1/2 for systems up to 2 MV and as much as can be got without too much expense above this. (See reference 2). For the output face of a 50 kV capacitor, this obviously cannot be overvolted to 100 kV but if a simple model of the output face is made, tracking tests can be carried up to the desired levels. It is necessary to put a small high voltage capacitor (several hundred pf's) where the capacity would be, otherwise a surface track starting across the face of the mock-up, would drop the HT terminal volts and choke itself off, something that would not happen in the proper arrangement. The mode of working is to find out where and at what level corona or tracking occurs and then try ad hoc experiments to raise these levels, experiments guided by physical pictures of the processes going on. By means of extra insulation, rounding metal surfaces, etc the tracking voltage is raised until either it reaches the desired safety factor, or until so many different tracking phenomena show up that they cannot all be beaten. In the later case the system is certainly safer than if it had just been built from scratch, and it is usually possible to make the weak region easily repairable and limit the effect of a track occurring at the now known weak point in the design. In one recent case one stage of a spark gap column designed to work at 80 kV was built and a couple of simple tricks enabled the tracking voltage to be raised to greater than 145 kV, the construction and tests taking about 4 hours to perform.

If the portion of the system has to work in a dirty atmosphere or in high humidity, then it is very desirable to get some representative dirt (swept off the floor of the laboratory) or to boil a kettle near by. Such tests will sometimes show that a tracking solution which works well in clean conditions is no good for dirty and/or damp real life working. In case of wind borne fine dust, face powder makes a good scaled substitute and is usually available in modest quantities from a charming nearby source of supply.

In testing a full scale system a relatively small number of shots at 20 or 30% above the maximum rated output of the system will disclose rapidly any weaknesses, which then can be corrected. While repairing a brand new system that has just tracked under an overall test it is worth bearing in mind that the fault would almost certainly have shown itself during the many shots of the systems use and that then it might cause more damage and lead to secondary faults elsewhere. Again the system can be fired at modest volts into short circuit to test the current capabilities of the connector, gaps, etc, typically a current two to three times the maximum expected being a useful overtest. The system is then examined for signs of burning at vulnerable plugs joints etc. Overtesting requires judgment and not inconsiderable willpower and courage but is a vital factor in obtaining reasonably trouble free use afterwards. Indeed some complex systems have never operated properly because the individual components and sub-systems failed more often than the number of sub-systems.

FAULT MODES

All systems malfunction at sometime if they are used at all extensively and it behooves the system designed to consider these occurrences. Usually components can be designed to take the fault mode energy deposition in charging resistors, etc without too much extra cost and effort. If not the component concerned can be made easily replaceable (consider the normal fuse link). Extra impedances can usually be added at a cost of a modest energy loss in normal operation, which however absorbs much greater fractions of the energy in fault mode operation. We normally add some resistance in series with the marx when this is feeding a pulsed high speed section to damp out the

353 (10)

marx ringing after the fast section switch has fired. This limits the current sloshing backwards and forwards in the marx and makes life much easier for the spark gaps and condenser. This is not strictly a fault mode operation but is a more general precaution which incidentally helps greatly in limiting fault mode damage. The system should ideally be operated in its likely fault modes and indeed during overvolt testing this sometimes happens incidentally. However not all faults are equally likely and this is impracticable in general. However certain faults are either inevitable or very likely and it should be ensured that the systems survive these either with no, or with easily repairable, damage.

The larger the system the more imperative it is to consider fault mode behaviour and, a sad fact but true, the less likely the system is to be intentionally tested in these modes. I know of one case where a 5 Megajoule system was intentionally fired in several fault modes, something which required real guts to do but which I am certain has paid off handsomely in trouble free usage.

Largely for amusement, reference 7, is included as an example of a possible system designed to work continually in at least one fault mode. I trust Hull University will soon be wanting to build systems of this size.

LECTURE NO. 5 REFERENCES

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